Section 5—Occupant Protection Advanced Technology

5.1 Current Safety Restraint Systems

Safety restraint systems in current vehicles typically include seat belts and an air bag system. A block diagram of a typical safety restraint system is given in Figure 5-1.

Current system components

Current air bag systems include one or more crash sensors, a diagnostic and control module, wiring, inflators, and air bags. The inflators and air bags are packaged in modules that are under protective covers in the center of the steering wheel (for the driver) and on the right side of the instrument panel (for the center and right front passengers). The crash sensor obtains data from the forces of the crash. Those data are processed to determine whether air bag deployment is desirable for occupant crash protection. If the decision is to deploy the bags, an electrical signal is sent to the inflator to generate or release gas to inflate the air bags.

Safety belts

Production safety belts for outboard occupants are universally three-point systems consisting of a soft-edged belt that crosses the lap and then the chest from a lower inboard attachment point to the upper outboard attachment point. The upper outboard end of the belt usually goes through a “D” ring mounted on the “B” pillar of the vehicle and down to a spring-loaded reel. This reel permits the belt to feed out to fit occupants and their movements, but takes up slack in the belt. The reel has a device that locks it when forces on the vehicle indicate the need for belt restraint.

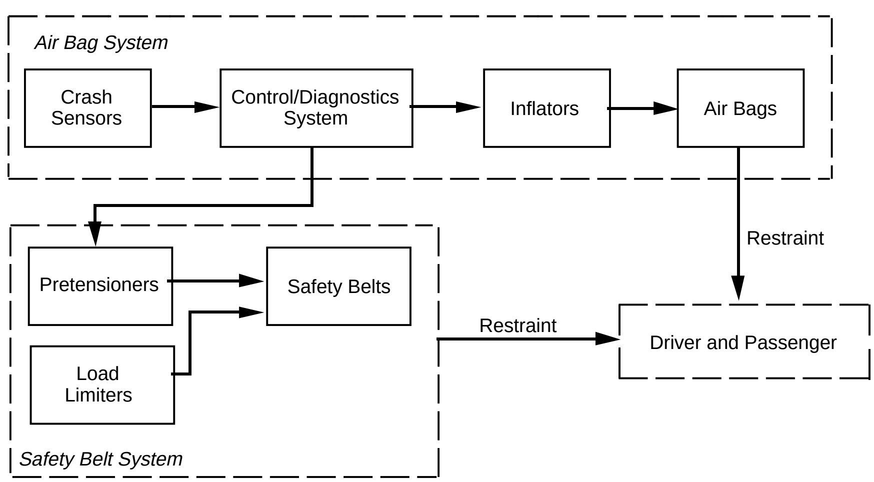

Figure 5-1. Schematic Diagram of Current Production Restraint System

Pretensioners and load limiters

Some safety belt systems have pretensioning devices that pull 10 cm or more of belt back into the reel to reduce slack and improve restraint performance. Pretensioners are triggered by crash sensors similar to those that trigger air bags. Some belts also have load-limiting devices that release belt webbing in a controlled manner to reduce peak forces on the occupant.

Automatic safety belts

For several years in the late 1980s and early 1990s, some manufacturers used automatic safety belts to meet the requirements of FMVSS 208. These systems typically moved a belt into place across the chest when the door was closed and had manual lap belts to complete belt protection. A few manufacturers used door-mounted manual lap/shoulder belts to meet FMVSS 208 under the pretext that these belts could be left buckled when the vehicle door was opened and closed, providing automatic protection. In fact, users of these vehicles almost never used the belts in this “automatic” mode. These belts often had poor geometry with outboard mounting points too far forward, permitting excessive occupant motion during a crash.

Electromechanical crash sensors

Crash sensors are all-mechanical switches, electromechanical switches, and/or electronic inertial sensors. Electromechanical switches are typically used in combinations of discriminating and safing sensors located at different points in the forward part of a vehicle. This is sometimes called multiple-point sensing. The discriminating sensors most often are highly damped electromechanical switches that activate at a specified change in velocity. These discriminating sensors typically are placed close to the front of the vehicle in the crush zone in order to provide information early in a crash. Low-threshold safing sensors are used to prevent unwanted air bag deployment from localized damage.

Single-point electronic sensing

A recent trend has been toward single-point or multipoint electronic sensing. In single-point sensing, an electronic accelerometer typically is placed in the occupant compartment. Its signal is processed by algorithms to determine crash severity. The intent is to make an early determination (from the forces transmitted to the occupant compartment), while maintaining immunity from signals that are not relevant to the need for occupant restraint. Electronic accelerometers are also used as multipoint sensors.

Air bag module mounting

The size and geometry of the frontal air bag modules are different for the driver and passenger. The driver-side unit must be packaged in the steering wheel. The passenger-side unit must be larger to accommodate a larger air bag and is packaged in the right side of the instrument panel. Different vehicles have alternative mounting positions to improve air bag performance. In some vehicles, the passenger air bag is deployed in an upward direction to reduce loading on out-of-position passengers during deployment. Mounting of the side impact air bags is usually in the "B" pillars, doors, or the seat.

Inflators

Typical components of a current production inflator include an initiator, gas generator, filter/heat sink, and nozzle. The gas generator typically has only a single stage with fixed output. Traditional propellants are sodium azide or nitrocellulose. Hybrid gas generators using stored gas and a solid propellant heating element have recently been introduced in the passenger air bags of some vehicles. The filter/heat sink removes particulate matter and reduces the temperature of the output stream from the gas generator before it enters the air bag. The nozzle directs the inflator output stream into the air bag.

Air bags

Current air bags are usually made from multi-element sewn fabrics. The bag fabric is folded into the module housing. The type of fold used in the packaging of the air bag helps determine the bag geometry during the inflation process. Two schemes currently used are Petri-folding (P-folding) and Leporello-folding (L-folding). With the L-folding technique, the air bag is folded in accordion-type layers to a package that generally is located directly above the inflator. With the P-folding technique, the air bag is configured in the form of several concentric ring folds around the inflator. Tethers often are used to provide control of bag geometry during deployment. Vents control the release of gas from the air bag and permit the air bag to deflate after a crash. Current vents are fixed in size and remain open during the entire deployment.

Seat belts

The primary safety restraint system on current vehicles is seat belts. They include a three-point belt attachment with a single belt retractor and soft-edge webbing. The belt has a cable end-release buckle and free-running tongue. Specific belt designs vary considerably among current vehicles. Some new vehicles incorporate belt adjustment seat mounting, webbing grabbers, webbing elongation tailored to air bags, load-limiting devices, belt pretensioners, and belt sensors (to alter air bag deployment thresholds) into the seat belt system. Current belt pretensioners are low-output devices designed to eliminate belt slack during a crash event.

5.2 Advanced Safety Restraint Systems

5.2.1 Introduction. Team members have had numerous technical exchanges with automobile manufacturers and system and component suppliers about technologies that may be used in advanced safety restraint systems. The organizations contacted are listed in Appendix A. In addition, JPL distributed a questionnaire to all OEMs and suppliers who were known to be developing advanced air bag technology. The questionnaire is given in Appendix B.

Reporting of technology capability limited by confidential information

Most of the information received was confidential, including all data that supported performance claims. The advanced technology descriptions and capabilities presented here reflect the information and data gathered, but do not include details protected by the confidentiality agreements. Therefore, the descriptions do not include comparisons among competitors' systems or detailed descriptions of specific component capabilities. Instead, generic capabilities of technology type are presented. A summary of the technologies investigated and their characteristics is given in Table 5-1.

The technology survey and conclusions derived from it are based on contacts with a limited number of vehicle manufacturers and suppliers. The state of the art of advanced air bag technologies is in a high state of flux, and the technologies discussed in the report, as well as other technologies, may advance more or less rapidly than indicated in the report.

Based upon our discussions, we envision that future safety restraint systems may include advanced seat/seat belt systems, advanced inflatable restraints, and numerous sensors (for detection of precrash events, crash severity, occupant type/proximity, and safety belt status). These systems will need an advanced control system to monitor all of the sensor information and deploy selected elements of the safety restraint system (based upon an internal algorithm).

Future safety restraint systems

In an advanced safety restraint system, the control system will: (1) detect/determine crash severity from precrash and crash sensors; (2) detect position and size of occupants using data from a variety of occupant sensors and/or weight sensors; (3) detect belt use; (4) detect the presence of rear-facing infant seats (RFISs) and front-facing infant seats (FFISs); and (5) use the above data to modulate the performance of the variable portions of both the safety belt and air bag systems (e.g., fire pretensioners, enable low seat-belt load limits, turn off the air bag, etc.). This system may require more processing power than is available in current air bag control systems, as the system will process more data from multiple subsystems in a shorter time. A schematic diagram of an advanced safety restraint system containing all of these elements is given in Figure 5-2.

Table 5-1. Advanced Technology Characteristics

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date*
Sensors Pre-Crash Sensing	These sensors provide remote sensing (electromagnetic) for early crash severity determination.	The potential here is limited. The ability to determine obstacle inertia has not been determined. The implications of system unreliability are not defined, but they are potentially serious.	These sensors could be available for MY2001.
Crash Severity Sensors	These sensors are electromechanical switches and analog accelerometers for determination of crash severity.	Critical capabilities already have been demonstrated. A move toward analog accelerometers (single-point sensors) is underway. This reduces cost/complexity.	These sensors are available now.
Sensing Diagnostic Modules/Crash Algorithms	Improved algorithms are aimed at reducing discrimination times and unintended airbag deployments. Evolutionary design includes improved hardware compatible with an increased number of sensor inputs and restraint firing loops.	There is unclear potential for significant improvement. Details of current system performance are unavailable to JPL due to confidentiality concerns by companies.	Development here is ongoing.
Belt Use Sensors	These sensors determine whether or not a safety belt is being used.	Hall-type sensors have been developed.	These sensors could be available for introduction into vehicles by MY2000.
Belt spool-out sensors	These sensors aid in determining occupant size.	These sensors with seat position sensors could provide approximate information on occupant size and proximity, but JPL knows of no plan by industry for their use.	These sensors could be available by MY2001
Seat Position Sensors	These sensors could be used to estimate driver size and proximity to the air bag and passenger proximity.	These sensors would be a surrogate for occupant presence and proximity sensors, but would only provide approximate information.	These sensors could be available for MY2000.

* Technology readiness dates are those dates when production subsystems could be ready. Implementation into vehicles depends upon the OEMs' decision to include them and their technology deployment schedules, which could add one to three years to the model year readiness dates provided here.

Table 5-1. Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
Sensors (cont.) Occupant Classification Sensors	These sensors measure weight and presence for classification of at-risk occupants.	Weight sensors have fundamental inaccuracies and systemic errors. They have limited utility. Presence sensors show ability for occupant classifications. System reliability requirements are unclear. Child seat tags will provide the required performance. Required retrofit of existing child seats is an impediment.	MY2000 could see availability of weight sensors and presence sensors. Tags are available now.
Occupant Proximity Motion Sensors	These sensors involve remote sensing systems to provide range information between occupants and in-cabin hazards.	These sensors are useful for static OOP detection. The consequences of system unreliability are not well defined. Ultra-sonic/IR systems hold the greatest promise. Utility of dynamic proximity information is not well understood at present.	These sensors could be available by MY2000/2001.
Computational Systems/ Algorithms	Such systems record all sensor signals to determine/actuate restraint system response.	These might replace upgraded crash sensor diagnostic modules, as systems requirements expand. Hardware currently is available. Utility of currently envisioned advanced algorithms has not been demonstrated.	These systems could be in use by MY2000.
Inflators Non-Azide Propellants	These materials replace sodium azide propel-lants to improve gas generant properties (i.e., they are smokeless and odorless, and they have fewer particulates and lower temperatures).	These propellants have lower temperature gas with no particulates. This will permit use of lighter-weight air bag fabrics, which improve performance. Simpler inflator designs are possible.	Some non-azide propellants are now used; however, they have higher gas temperatures. Low vulnerability (LOVA) propellants should be ready for MY2000.
Hybrid Inflators	These inflators use high-pressure stored gas in conjunction with a pyrotechnic charge.	These inflators have more desirable gas generant properties (i.e., fewer particulates). There is lower variability in performance.	More use is expected by MY1999. Units with LOVA propellants could be ready by MY2000.
Heated Gas Inflators	These inflators use a combustible mixture of dry air and hydrogen gas under high pressure.	The gas generant is clean and environ-mentally friendly. These inflators permit use of lighter-weight air bag fabrics to improve performance.	These units are expected to be ready by MY1999.

Table 5-1. Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
Inflators (cont.) Multistage Inflators	These systems use two separate inflators packaged as a single unit, or two separate pyrotechnic charges with a single inflator.	These inflators permit stages of air bag deployment depending on crash severity and occupant characteristics. Inflator performance variability could overshadow the potential advantages.	Two-stage inflators could be ready for production in 1998.
Inflators with Tailorable Mass Flow Rate	These systems provide control of inflator output in near real-time.	With appropriate sensor information, this technology would permit control of air bag deployment depending on crash severity and occupant location and characteristics.	These inflators are under development.
Air Bags New Fabrics and Coatings	Fabrics and coatings that are more flexible, lighter in weight and have lower permeability are now available.	These fabrics permit use of lower output inflators. Lower mass should reduce punchout forces on OOP occupants. These materials simplify bag folding techniques. Lighter-weight fabrics are less tolerant of particulates and high temperature gases.	Technology has been demonstrated with inflators having low particulates and lower gas temperatures. These materials could be incorporated with hybrid inflators for MY2000.
New Woven Fabrics and Bag Construction	These materials use controlled fabric porosity and improved weaving techniques to reduce or eliminate bag seams.	Fabrics having controlled porosity with low variability could eliminate the need for discrete vent holes.	This is an evolving technology, which could be incorporated as product improvement.
New Bag Shapes and Compart-mented Bags	These alternatives involve air bags with multiple compartments, which inflate sequentially. Bags expand radially during deployment.	The first compartment can be pressurized much quicker to provide early occupant protection, with subsequent compart-ments maintaining the restraint force. This is especially beneficial to OOP occupants.	This technology could be ready for introduction in MY2000.
New Air Bag Venting Systems	These systems provide multilevel venting systems with discrete holes and continuously variable venting designs. Continuously variable venting designs would be controlled in near real-time based on available sensor information.	These systems provide pre-determined variation in venting depending on bag pressure. They provide rapid inflation of air bags (with no venting) to reduce occupant/air bag interaction. Continuously variable systems must be developed in conjunction with sensors and control strategies.	Multilevel systems could be available in MY1999. Continuously variable systems are being developed.

Table 5-1. Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
Seat Belt Systems Pretensioners	This technology involves high-output pretensioners to increase coupling between occupant and seat.	Maximizes ride-down distance for dissipation of the occupant's kinetic energy.	Pretentioners are in some vehicles now. Newer high-output devices could be ready in MY1999.
Load Limiting Devices	Single- or dual-level devices provide a fixed force level over the maximum occupant excursions. Continuously variable load limiters provide a wide variation of forces.	Dual-level load limiters can provide two-level selection based on knowledge of the occupant's characteristics. Further adjustability is provided by continuously variable devices.	Load limiters are in some vehicles now. Continuously variable devices could be ready in MY2000.
Inflatable Seat Belts	A portion of the standard three-point belt is inflated to augment the belt function.	These devices offer inflated cushioning and also provide some pretensioning of the seat belt. Air belts are less aggressive than air bags.	These devices could be ready by MY2001.

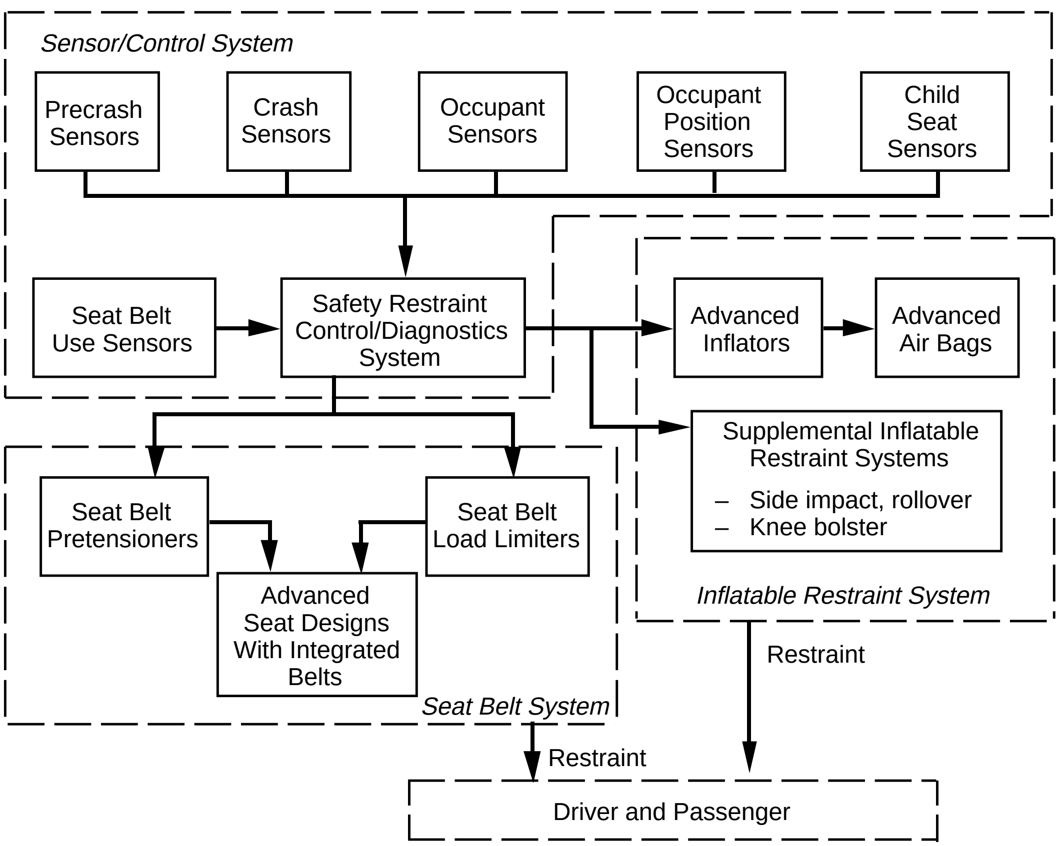

Figure 5-2. Advanced Safety Restraint System Schematic Diagram

5.2.2 Advanced Sensor Technology Development. Currently, the primary sensors in air bag systems are crash severity sensors. These sensors detect changes in the kinematic parameters (velocity and its derivatives) of the vehicle in response to a crash event and make a decision to deploy supplemental restraints (e.g., air bags) and/or enhanced primary restraints (e.g., seat belts with pretensioners). Many of the current limitations and liabilities of safety restraint systems are a result of insufficient crash and occupant information. Decisions by crash sensors to mitigate the hazards associated with very complex crash events are being made on the basis of a limited amount of data. Typically, only the first 15 to 20 ms of single-point crash sensor data (a time series with under 100 sample points) are used to discriminate between deployment and nondeployment events.

Limitations of current sensing: insufficient crash and occupant information

The general consensus in the industry is that restraint performance could be enhanced through the collection and use of other information. For example, restraint designers believe that a knowledge of the precrash environment, of occupant types/sizes and proximity to in-cabin hazards, and of the use of safety belts allow a restraint system response that is better tailored to the specifics of a given crash. In short, the view of restraint experts is that better crash information early in a crash can be used to generate a more appropriate response.

Need for more information is to be provided by new sensors

Additional sensors will be required to provide this enhanced information. The added sensors will enhance, but not replace, crash sensor information. Detection of an actual crash will remain a basic requirement for air bag deployment in the future.

Current advanced safety restraint sensor development is largely a process of evolution. Crash severity sensing technology began with multiple electromechanical switches, actuated at a specified vehicle velocity change [e.g., V = 16 km/h (10 mph)]. The current state of the art is analog accelerometers with data processing algorithms. These provide more accurate discrimination between crashes that do, or do not, require deployment. Ongoing refinements in crash-sensing systems are geared primarily toward "parameter pushing." That is, evolutionary development provides incremental improvements to discrimination time values and immunity from extraneous information.

Some sensors will evolve; others require the application of new technology

A significant knowledge base exists from which advanced technology improvements can develop. Some advanced systems, however, will require the development and application of completely new technologies. The most active area of new technology development has been directed at elimination of inflation-induced injury (I^3) from air bags. The primary focus has been on the detection of at-risk occupants in order to suppress air bag deployment. The industry is developing sensing technology to determine occupant characteristics and proximity to deploying air bags.

In the future the inherent speed of many proximity sensors should allow dynamic sensing of occupant proximity to in-cabin hazards. This capability should permit finer control of the response of the restraint system, which will improve the efficacy of the restraint system, in addition to mitigating its negative effects. To this end, precrash sensing has been proposed as a potentially important safety enhancement. Precrash sensing could provide both crash avoidance capability as well as earlier prediction of crash severity, which may allow earlier restraint system response. (Refer to Section 4.1.1.1.) In general, the requirements driving this new technology development are not as clearly understood, relative to crash sensors, because of the lack of critical field performance data.

Seat belt sensing technology is becoming more reliable. Thus we envision that seat belt status information will begin to play a role in the deployment of active restraints.

Advanced sensor categories

The advanced sensor technologies investigated by JPL are divided according to function. The categories are:

1. Precrash sensors
2. Crash severity sensors
3. Diagnostic modules and crash detection algorithms
4. Occupant size or mass sensors
5. Occupant proximity and motion sensors
6. Safety belt status sensors
7. Computational systems/algorithms

Precrash sensors provide advanced warning

5.2.2.1 Precrash Sensors. Precrash sensors could provide advanced warning of an obstacle. This information could facilitate crash avoidance or earlier air bag deployment. Information from the precrash sensor could prepare a crash severity sensor to make an earlier decision on whether or not to deploy the air bags. If an obstacle is seen by the precrash sensor with a high closing speed, the crash sensor could be programmed to deploy the bags as soon as major deceleration is measured. On the other hand, if no obstacle is observed by the precrash sensor before the crash sensor detects deceleration, the system may be programmed to require a higher level of deceleration or change of velocity before the air bags are deployed.

Precrash sensors are likely to be used first as part of a smart cruise control that adjusts the speed of the vehicle for traffic conditions. The industry is pursuing both radar and visible imaging technologies for precrash sensors.

Radar systems

One supplier's radar system uses dual antennas, operating as a phased array. Millimeter-wave pulses are transmitted into the region in front of the vehicle. Backscattered pulses are detected, with their travel time providing an indication of the range of the reflector. The received amplitude provides information on the size and composition of the reflecting object.

Another supplier utilizes a 1-mm^2 chip that contains all of the transmitter functions. The system is approximately 6×9×1.3 cm and fits under the front bumper. It senses an object within 3 meters and tracks speed and distance, thus providing distance and time-to-impact data to the crash recorder. It has been tested with many types of obstacles, road objects, and in various weather conditions.

The transmitted beam shape depends upon the application. Narrow beam shapes (high f-number optics) are used for automated cruise control, where long-range forward-looking capability and low-lateral interference are important. Short, wide beam shapes (low f-number optics) are used for precrash sensing. Here, sensing ranges of 0.5 m in front of the vehicle allow determination of closing velocity at least 100 ms prior to first impact. This provides sufficient early warning.

Sensor cannot resolve obstacle mass

The precrash radar system, through its data processing algorithm, can provide an indication of obstacle size by determining the solid angle subtended by the reflector. The ability to determine the inertia of the obstacle is not clear. No supplier could articulate any capability to resolve obstacle mass. The radar system consists of antennas/power electronics remotely located (at the front of the car) that interface with a separate electronic controller. It is not clear whether the controller's function could be implemented on the standard crash sensor/air bag controller system or whether a separate, dedicated system is required. One supplier quoted a cost for this system in the \$150–\$200 range, installed. Another said that it would be \$100 or less. Systems could be ready for introduction in MY 2001 cars if OEMs decided to do so immediately.

JPL's investigation found at least five precrash sensor development programs. Two suppliers provided detailed information.

5.2.2.2 Crash Severity Sensors. Crash sensors are physical transducers that convert variations in kinematic parameters (vehicle velocity and its derivatives) to an electrical signal. Two general types are in use: electromechanical switches that close an electrical contact at some specified signal level (typically the change in vehicle velocity) and analog sensors that provide an output voltage proportional to signal input (such as acceleration). Switches provide essentially a single response, while accelerometers provide a moderately large time series of data (a few hundred points) during a crash event.

Two types of crash sensors

Electromechanical switches typically are overdamped spring-mass systems that trigger after a specific change in vehicle velocity. Switches are placed in a number of areas, including the vehicle's frontal crush zone. In this way, the switch will trigger at a specified signal level, well in advance of that signal level being felt in the occupant compartment. The technology is mature. JPL's work uncovered no significant advanced development work in this area.

Electromechanical sensors

There was one new application of the technology worth mentioning, however. One developer reported a distributed crush switch to be located at the extreme front of the vehicle where it would provide early crash severity data over a wide angle. This system could detect narrow-object impacts and highly offset crashes that would not trigger the main crash sensor until later in the collision. Before the main crash sensor could detect the crash, the occupants might move into the keep-out zone. These sensors could work with the main crash sensor like precrash sensors.

The size of the electromechanical sensors (a few cm^3), although small, is an issue when compared to alternative technologies. One limitation, communicated by end users, was the difficulty in reliably raising the threshold of some present switch type sensors, because of limits to damping factors achievable with current geometries.

Analog accelerometers use a number of sensing technologies (piezoelectric crystals, silicon-based piezo-resistive, and variable capacitance) to develop extremely small (< cm^3), low-cost sensors. The scale factor and full-scale range of the accelerometer can be adjusted easily during manufacture, and nearly all sensors have the capability for electrical self-testing. Because of this, accelerometers are seen to have advantages, especially from a systems perspective. At this time, accelerometer technology is fairly well developed. Further development is geared mainly toward price reduction and data processing.

Accelerometers

Electromechanical sensors are being replaced by single-point accelerometers

The trend is toward replacing distributed electromechanical crash sensors (switches) with single- (or dual-) axis accelerometers located in or around the passenger compartment. They are placed in areas that are likely to remain undeformed during a crash and that do not resonate during the crash. A common mounting is near the centerline of the vehicle behind the firewall on a structural component near the toe board where it is protected from the elements. Multiple crush-zone sensors are being replaced by a single analog accelerometer or single-point sensor. The rationale is three-fold: to reduce costs associated with multiple sensors and their installation, to improve reliability by minimizing wiring to areas vulnerable during a crash, and to improve the flexibility of the system. The latter point relates to the fact that an analog accelerometer provides a much larger volume of data with which to predict ultimate crash severity.

Processing of these data allows a prediction of severity on a time scale similar to that of a crush-zone-mounted switch, except for soft vehicle structures in narrow-object crashes, and possibly others. Deployment thresholds may be adjusted through software rather than the mechanical modification required for electromechanical switches. Placing the sensor in the occupant compartment simplifies installation (i.e., reduces its cost) compared to the crush-zone- mounted sensors. Because the sensor is situated in a *relatively* benign environment, there is less risk of malfunction of the sensor and its wiring. Although single-point sensing is becoming quite common, there are certain vehicle platforms that will still require multiple sensors. This is because of the inability of a single sensor to provide early crash detection for all crash scenarios.

Sensor performances are good, but the challenge is integration with the vehicle, which has a variable crash response

The strong consensus of the companies surveyed is that the performance of the sensor element itself is very good. The sensors provide accurate triggering (in the case of switches) and high-fidelity records of acceleration (in the case of analog accelerometers). The main challenges involve its physical placement on a particular vehicle and, most importantly, the processing of its data. Sensor placement is a critical step in the "tuning" process, where the vehicle crush characteristics over a wide range of crash pulses must be accounted for. This is critical for crush-zone switches.

5.2.2.3 Control Modules and Crash Detection Algorithms. Advanced development of crash severity sensing systems is concentrating on digital algorithms for providing early, accurate restraint deployment decisions. These algorithms are applied to the data from analog accelerometers in single-point crash sensing systems. The analog signals (voltage vs. time) from the crash sensing accelerometer are digitized by the module, typically at 8- to 10-bit resolution. The digital data are processed in real time, and the processed data are compared to a threshold to determine whether or not a restraint should be deployed.

Single-point sensing presents a challenging data processing problem

With single sensors mounted in the occupant compartment, this task involves determination of crash severity using a very small amount of low-amplitude data. For example, as shown in Appendix C for a representative AAMA crash pulse, a deployment decision must be made when the velocity of the occupant compartment has changed by only 3.4 km/h (2.1 mph). This can be compared to the approximate 16 km/h (10 mph) change in velocity seen at the same time by sensors (electromechanical switches) located in the vehicle crush zone. Although single-point analog accelerometer sensing is attractive from a systems standpoint, it presents a challenging data processing problem. A decision must be made at a point where the kinematic parameters are very small.

Suppliers are working on advanced algorithms for improved crash severity prediction

All developers are working toward the goal of providing timely decisions for a variety of crash pulses (including long duration events), while reducing the number of unwanted deployments. Most advanced approaches use either physical or pattern recognition algorithms (or combinations of both) to improve this determination. Physical algorithms attempt to calculate and evaluate physically relevant quantities (such as acceleration and jerk) that strongly correlate with crash severity. Pattern recognition techniques operate on the premise that particular crash events have unique signatures, and that these signatures can be used to discriminate crash severity. It was not clear to JPL which of these approaches is superior. All suppliers view their algorithms as valuable intellectual property, so it was not possible to get more than a cursory glance at any one approach.

The OEMs provide discrimination time requirements for each of a number of crash types [e.g., 48 km/h (30 mph) rigid fixed barrier (RFB), 40 km/h (25 mph) deformable offset barrier (DOB), pole]. Requirements are also provided for nondeployment in a variety of events [such as crashes with ΔV in the forward direction <14.4 km/h (9 mph), rough road driving, and undercarriage strikes]. The standard procedure for developing single-point crash algorithms is for the OEM customer to provide a set of acceleration data and required deployment times for various events (both deployment and nondeployment) for a given vehicle platform. The suppliers develop algorithms for processing these data to make proper deployment decisions with the required timing.

Some 7 to 12 types of different events must be considered, and often there are multiple data sets for each event, reflecting in part the observed variations in crash pulse. The algorithms must handle these variations consistently. Suppliers indicate that developing and testing these algorithms to handle this number of events is a large, time-consuming task. It is JPL's view that the extent of variation in real-world crashes is not fully accounted for in these developments.

Provision for crash variability is a challenge

As pointed out in Section 4.1.5, the recorded variability of crash discrimination times is large in some types of collisions with soft objects, such as the sides of cars. This may indicate that the current algorithms, while finely tuned for certain obvious crash pulses [e.g., 48 km/h (30 mph) RFB per FMVSS 208], may have limitations in some real-world crashes. An alternative viewpoint is that the observed deployment time variability in some events is due more to variability in the vehicle crush characteristics than to shortcomings in the algorithms. The vehicle crush variability results in variability in the signals recorded by the crash sensor.

In JPL's view, the current algorithm development process, relying on "representative" data sets, would benefit from the inclusion of this variability to a greater degree. One supplier articulated clearly that OEMs provide insufficient data to account for this variability. Providing these data is obviously a large and complex task. However, further improvements in crash severity sensing probably will require it. One supplier is attempting to include such variability into its system testing. In this case, random fluctuations are introduced into the high-frequency portion of the signals applied to a test thruster system.

The effects of this variability on the performance of the algorithm could be monitored during lab testing and subsequently minimized. This appears to be a good idea; however, an obvious future step would be to extend the technique to lower frequency in order to better simulate the effects of fluctuations in vehicle crush characteristics, for example. Still, the acknowledgment of the effects of these variabilities and the attempt to understand them is unique to this supplier. The importance of crash sensing to the overall performance of the restraint system makes it clear that any testing must include the crash sensor system. For example, compliance testing on sleds using generic crash pulses and a preset trigger time has limited value as it does not test the vehicle crush characteristics, the crash sensor system, or their interaction.

JPL discussed the development of advanced algorithms with six different suppliers. A consistent response to questions regarding their ability to provide timely crash discrimination for a range of crash pulses was that "we are able to meet the requirements of our customer." The only unsolved problem mentioned by a subset of these suppliers was accurate determination of pole crashes. Here the obvious problem is an inability to detect this event, with its soft initial pulse, early enough to safely deploy the air bag. The suppliers provided very little data to support their performance claims. The data that were provided generally were the results from applying their particular algorithms to the typical data sets provided to them by their OEM customers. The extent to which the suppliers of crash sensing algorithms participate in actual crash testing is unclear. There is obviously some crash testing done by OEMs, but no supplier provided information on the variability in discrimination times observed in actual crash tests. The numbers they did provide appeared to be based on OEM-supplied data sets.

Pole crash prediction is a problem

No supplier was able to provide specific reliability data for in-field performance. Real-world performance data from vehicle crashes are critical to understanding reliability in the field. The suppliers indicated that they do not have detailed numbers relating to field performance. At least one OEM, however, has investigated variability of deployment timing (see Section 4.2.1) observed in crash testing. The suppliers were not prepared to discuss the importance of field data.

No field reliability data available

Crash sensing modules are evolving to incorporate the requirements imposed by new restraint systems. This includes adding firing loops to control pretensioners, multistage inflators, and side impact air bag modules. Additional sensor inputs are being provided by suppliers to accommodate additional information from, for example, seat-belt sensors and occupant type/proximity sensors. Similarly, air bag deployment algorithms are being modified by suppliers (only slightly) to incorporate this information in order to provide the first types of "tailored response." The technology is available to incorporate increased data processing required by future systems. The quality of crash sensor data and the methods by which the system response is determined are uncertain in current systems.

Additional capabilities

Future improvements in crash severity sensing systems will largely be evolutionary. A large number of single-point systems are currently in production vehicles. Introducing new performance features to existing products is a simpler process than introducing completely new systems. This is why improvements to crash sensing systems and their incorporation into vehicles will be a continuous process. Most suppliers indicated that these improvements add little additional cost.

5.2.2.4 Occupant Classification Sensors. Much of the advanced sensor development has concentrated on occupant detection. This includes classification of the occupant (size and/or weight) and the detection of specific cases (rear-facing or front-facing child seats, driver drowsiness, and so on). The initial use of this information is for air bag suppression or depowering to eliminate air bag-induced injuries. A more distant goal is to finely tailor the restraint system response to the specific characteristics of the occupant. For example, knowledge of occupant size or weight could allow different system responses for children, 5th-percentile females (5% F), 50th-percentile males (50% M), and 95th-percentile males (95% M).

Sensing occupant characteristics

Detecting occupant type is, by all accounts, a difficult task. It is made more difficult by the apparent lack of detailed performance requirements for the technology. Some OEMs have provided limited performance requirements related to occupant detection for air bag suppression. These include requirements for discrimination between rear-facing infant seats (RFISs) and normally seated adults, for example, but they stop short of providing detailed technical requirements on critical issues such as reliability. The lack of clear requirements is limiting technology development.

Occupant classification sensing technologies fall into four main categories: (1) weight sensors, (2) presence sensors, (3) seat position and belt spool-out sensors, and (4) tag-based systems.

Four types of occupant classification sensors

5.2.2.4.1 Weight Sensors. The purpose of weight sensors is to measure the mass of an occupant by measuring forces on the seat. In addition, some approaches measure weight distribution on the seat in order to improve the ability to classify occupants. There are many obvious limitations of a weight sensor approach, including the inherent inaccuracy of inferring mass and seating position from distributed seat forces. A weight sensor probably cannot account for the multitude of seating configurations for any one occupant. For example, the distribution of supporting forces between an occupant's upper torso (on the seat) and legs (on the floor) can lead to large inaccuracies. Additional forces (such as from seat belt tension) can also cause variability. Finally, tilting of the occupant (due to variable seat back angle) relative to the gravitational vector leads to inaccuracies.

Causes of weight sensor inaccuracies

Despite these limitations, the simplicity of a weight sensor, and the importance of knowledge of occupant mass, have led to a number of developments in this area. Mercedes-Benz offers a right front passenger seat sensor that shuts off the passenger air bag when the seat is loaded at less than 30 kg, for example. NHTSA's consideration of an under-30-kg air bag suppression requirement also has spurred development.

Types of weight sensors

The majority of sensors use resistive strain gauges that provide a resistance change proportional to sensor strain. This strain is proportional to stress applied to the element, leading indirectly to a measurement of weight. Strain sensor technology is highly evolved: thick film sensors are available on flexible substrates, allowing integration into a wide range of structures. Separate sensors can be distributed over the same substrate in order to measure stress distributions. The technology is very durable and extremely cost effective.

A second sensor approach uses a monolithic pressure sensor to measure the load-dependent pressure increases within a sealed gas bag. In some cases, the strain sensors are placed near the seat surface, just below the trim, while in others they are placed deeper into the seat. Both placement locations obviously can be affected by elastic forces within the seat itself. In addition, either transducer type (strain sensor or pressure sensor) will have a finite contact area dependence. One proposed solution is to use similar strain transducers as load cells to measure the total force at rigid support points in the seat frame. In either case, incorporation of weight sensors may require modification to seat design, seat track design, and seat belt design in order to limit systemic measurement errors.

All suppliers contacted understood (and to a limited degree would communicate) the limitations of their technologies. A common caution was that the weight information "is used only to augment information from a suite of sensors. By providing even coarse weight information (i.e., small or large), we can improve the response of the smart restraint system." The problem with this view is that inaccurate information cannot realistically play a significant role in adjusting the restraint system response. No suppliers could provide useful numbers on system reliability for weight sensors. They provided no detailed performance data on resolution and accuracy.

Testing provided poor results

Some OEMs have performed comprehensive evaluations of various weight sensors relative to their use for air bag suppression. They performed a number of trials with a range of occupant types [(RFIS, FFIS, 6-year-old anthropomorphic test dummy (ATD) in booster seat and regular seat, 5% female ATD, 50% male ATD, and various live child and adult occupants)]. The objective was to measure the ability of weight sensor systems to classify these occupants. The tests were done under static and driving conditions, both belted and unbelted, in a range of seat configurations. Their conclusion was that no system would provide a reasonable capability for classification. Particularly troubling was the common inability to distinguish between child seats and 5% females and to distinguish children. Live occupants presented classification problems for some systems. With some systems, there was a large degree of variability within occupant classes, large enough to cause overlaps between occupant categories. These generally poor results were enough to dissuade further extensive development by many suppliers.

Weight sensors are inherently inexpensive; however, integration costs may not be. Most suppliers indicated they could supply weight sensors for MY 2000 vehicles, which would require immediate implementation discussions with OEMs who currently view the technology as inadequate.

5.2.2.4.2 Presence Sensors. A wide variety of sensing technologies has been applied to the remote detection of occupant presence and type (e.g., RFIS). Each technology attempts to "image" an area in and around a seat and provide a classification of the occupant from this information. Technologies used include passive and active infrared, superaural acoustic, capacitive (electric field), radar, and visible imaging. The primary development goal has been to detect and distinguish grossly at-risk occupants (e.g., RFISs) from normally seated adult passengers. It does not appear that classification of adult occupants by size has been a major performance goal.

Ultrasonic presence sensors

Ultrasonic (acoustic) sensors are used in a number of systems. Acoustic pulses are transmitted from a set of 3 to 4 transducers. The transducers may be placed in the instrument panel, overhead console, and the trim around the A- and B-pillars. The pulses undergo reflections in the occupant compartment and are detected by the same transducer. Time-of-flight considerations limit system repetition rates to a few msec. Analysis of the echo signal, as a function of time, allows detection of the presence and range of multiple objects in the beam pattern. Multiple sensors provide the capability for classifying complex objects (e.g., RFIS) according to their echo patterns. Pattern recognition algorithms are used to generate these classifications.

One clear limitation is that unintended reflectors (books, newspapers, body extremities, etc.) that approach close to the transducers will block the signal. In theory, the use of multiple transducers provides some relief from this. OEM tests of ultrasonic-only systems indicate that they are very effective (stated at 100%) at static detection of an occupant in the seat. The detection of RFISs/FFCSs has been less successful (reported to be 70–95%). The required performance levels are unclear at present.

Infrared presence sensors

Infrared (IR) systems use either passive imaging of thermal signals with detector arrays or active ranging using near-IR sources (LEDs) and detectors. By itself, thermal IR imaging provides information of human presence and motion, but it is not used extensively for classification. Active IR systems are capable of providing ranging information at high speed, and with multiple channels, generating target-specific patterns. Unfortunately, IR systems are easily blocked by passenger clothing and accessories and are sensitive to surface properties of the target. OEM tests of selected IR-only systems have shown success in detection of occupant presence (100%) and RFISs/FFCSs (90%).

Combined acoustic/IR presence sensing systems

More advanced approaches are attempting to combine ultrasonic and IR technologies. One leading supplier is relying on multichannel acoustic ranging coupled with IR imaging to improve detection efficiency. The fusing and interpretation of data from multiple sensors (a considerable data processing problem) is seen by many groups as the best way to provide reliable occupant detection, even under continuously varying conditions. Many of the numbers quoted above for RFIS detection involved fairly well-controlled experiments. The real difficulty occurs in detecting a wide variety of occupant types in the presence of real-world variations. Multiple sensor approaches appear to provide the best capability for handling this.

Capacitive presence sensors

The third primary technology is capacitive sensing. This technology type senses the dielectric loading of an oscillating electric field set up between sets of electrodes. A dielectric body (a human) changes the field distribution. This change can be detected in a number of ways—for example, through measurement of the variation in the displacement current between the fixed electrodes. In this manner, the impedance (or capacitance) of the object can be detected. The fixed electrodes can be placed in a number of locations (IP, steering wheel, headliner, or seat cushion/back). While primarily used to measure proximity, the approach can provide classification. One supplier uses a set of four electrodes in the seat. Through a multiplexing approach in which one electrode is used as a transmitter and another as a receiver, a set of eight separate capacitance measurements can be made, each representing a unique dielectric path through the object. Analysis of these data allows some characterization of occupant type. OEM tests have shown some utility in detection of RFISs as well as good discrimination between small and large adult ATDs.

Expected production costs range from between $25 and $75 for this technology. The cost of integration is highly dependent on sensor location, however. Most suppliers indicate potential production readiness in MY 2000; actual model year implementation would be later and would be determined by OEM acceptance.

5.2.2.4.3 Seat Position and Belt Spool-out Sensors. Driver-side seat position sensors can provide some indication of the size of the driver. They offer a surrogate for more direct measurement of driver weight or size, compared with the weight and presence sensors discussed above. They could be less accurate, but could be available sooner than the other sensors. Only one supplier mentioned work on this type of sensor, and very little information about its design or performance was provided. Hall-type sensors would be one approach for providing seat position.

Belt spool-out sensors can provide some indication of both driver and right-front passenger size, if coupled with seat position sensors. Right-front passenger size determination would be less accurate than that of the driver size, because the passenger seat position could not be correlated with passenger size. No supplier mentioned this sensor type, and we have no information on the expected accuracy of measurement. We do not know if spool-out sensors would be accurate enough to determine if an occupant is out of position.

The use of these two sensors would, of course, be an improvement over the current system, which has no occupant sensors. JPL would require additional information and need to conduct further analysis to determine the potential of these two sensors.

Tags for RFIS detection

5.2.2.4.4 Tag-Based Systems. Other approaches to the detection of specific at-risk occupants, such as those in RFIS, have been developed. These include magnetic and electromagnetic tags attached to the child seat, either during manufacture or as part of a retrofit. The detection of a tag causes automatic suppression of an air bag. This technology has received considerable scrutiny, especially in light of plans to install air bag cutoff switches in certain vehicles. The availability of automatic tag systems could alleviate the need for operator intervention (via a switch). This may reduce the effects of operator error in specific cases. A number of technologies have been developed for this purpose. Most systems include transmit–receive coils (antennas) located in the passenger seat. The child seat contains a specific tag that modulates the electromagnetic field generated by the transmitter. The modulated field is detected and analyzed. The tag is passive (unpowered).

Tags for RFIS detection may be sensitive to childseat placement

There are a range of tag technologies. Some carry a unique code that is used to modulate the field in a specific manner. This approach theoretically reduces the error rate associated with detection. Specifically, it reduces the likelihood that a spurious signal could disable the air bag when a child seat is not present. On the other hand, there is general concern by OEMs over sensitivities of these systems to placement of the child seats, and whether improper placement could cause the system not to recognize a seat. This appears to be significantly less of a problem than the detection/discrimination requirements of either the weight-based sensors or the presence sensors discussed above.

Retrofitting car seats with tags could be a problem

JPL was not provided any substantial information on these systems by suppliers. Most of the information was provided by the OEMs, and the impression received was that this technology is not currently being considered for application by OEMs. One negative aspect is the need to retrofit existing car seats with tags and the potential consequences of the failure to do so. Based on JPL's technical judgment, this technology would carry costs similar to capacitive presence sensors. Its readiness has been demonstrated in Europe (Mercedes-Benz currently offers such a system).

5.2.2.5 Occupant Proximity/Motion Sensors. Occupant proximity sensors are intended to detect occupant position relative to in-cabin hazards. The first application is for air bag suppression or attenuation for static out-of-position (OOP) occupants. This is to mitigate the air bag deployment dangers for those individuals who are in the keep-out zone at the time of the signal to deploy the air bag. This application has commanded the largest amount of technology development.

Application of proximity sensing

A longer-term goal is to use real-time position information to modulate restraint deployment in order to improve its performance. This could include air bag suppression/attenuation to mitigate air bag-induced injuries for dynamic OOP occupants (those who have moved forward due to vehicle decelerations prior to and early in the crash sequence). As described in Appendix C, the use of dynamic proximity information for modulation of a restraint is problematical, due to the finite time period for air bag inflation.

One simple, but important, piece of information that can be provided by a proximity sensor is the initial occupant position. Knowledge of the initial position allows, for example, more precise determination of occupant kinematics, using only a single-point accelerometer. This approach would apply to those crash sensing algorithms that calculate and use unrestrained occupant displacement in crash discrimination. The proximity sensor data establish the initial occupant position, something a crash sensor cannot do.

Requirement information is lacking

Requirements for proximity sensors are lacking. No supplier was able to state what measurement range was required for static OOP sensing, nor was there any information provided regarding required resolution/accuracy for these measurements. As noted in Appendix C, these requirements are air bag/inflator-specific. This lack of data may indicate that the suppliers and OEMs have not investigated these parameters in detail. Neither provided much information on reliability requirements. Quantitative information on the effects of various failures was not provided in any detail by either the suppliers or the OEMs.

Quasistatic sensors could be implemented in the next 3 to 4 model years

To be fair, it is probably premature to expect a thorough understanding of dynamic proximity sensing requirements, as this is a future application of the technology. The short-term option is to implement quasistatic sensing within the next three to four years in order to better eliminate static OOP air-bag-induced injuries. Understanding the potential safety trade-offs associated with the proximity performance parameters will be critical as this technology nears production.

Proximity and presence sensing technologies are the same

Proximity sensor functions are derived from the same technology described above for presence detection. Technologies that provide range information (including passive and active infrared, superaural acoustic, capacitive, radar, and visible imaging) can calculate occupant proximity to air bag modules. The main technologies under development by the suppliers use acoustic and active IR ranging and capacitive position detection. One important characteristic of any technology used for proximity sensing is the effective point of reference on the occupant. That is, does the sensor detect the position of the *surface* nearest to the sensor or does the technology have volume-dependent sensitivities?

The critical distance is the one between the air bag module and the *closest surface* on the occupant. Technologies that are volume sensitive could only indirectly determine this distance, using knowledge of the size (volume) of the occupant. Volume-sensitive technologies lead to an inherent inaccuracy. Acoustic and IR ranging are inherently surface sensitive. The disadvantage of these sensors is that they can be blocked easily by thin objects in front of the occupant. Capacitive proximity sensors are not as easily blocked by such objects. However, their signals clearly depend on the volume of the occupant. Stated another way, the output voltage vs. nearest-surface distance for an analog capacitive detector may be strongly dependent on the volume of the dielectric object. Knowing the distance of the occupant's dielectric center to the IP or steering wheel is not sufficiently accurate. It is not clear that any mounting location could provide an accurate enough distance measurement. The basic problem of capacitive sensors may be mitigated through careful design of electrode geometry, but it must be addressed. The measurement limitations had not been seriously considered by many of the suppliers who are working with capacitive technology.

Visible imaging

Visible imaging has been explored by some groups as a potential technology for occupant ranging (proximity). The emergence of highly integrated, low-cost detector arrays, as well as higher-performance processors, has increased the applicability of this technology. One approach uses stereo imaging along with firmware-based algorithms for determining range information at each pixel in a composite image. State-of-the-art algorithms have enabled 100-ms update rates, potentially suitable for quasi-static proximity sensing. The resolution and accuracy of this approach is competitive with those listed above. Processing requirements and their cost are an obstacle at the present time. Image systems lend themselves readily to a number of other measurement tasks. It is envisioned by some groups that the same technology can be used for occupant classification and for precrash functions (potentially allowing for obstacle classification). This is a long-term opportunity, however. None of the technology observed in this area was ready for near-term (i.e., MY 2001) application.

Acoustic and infrared sensors hold the most immediate promise

Because of the position measurement limitation of capacitive sensors and the long-term prospects for visible imaging, it appears that acoustic and IR-based ranging systems hold the most promise for meeting short-term requirements for static proximity sensing. There are a number of suppliers developing these technologies. Most suppliers state that static systems would be ready for introduction in MY 2000 or 2001. Actual installation time depends on the OEM's decision to implement and the time to do so. Actual implementation would be two years later. Targeted costs are in the range of $35–$60 for either acoustic or IR-based systems. Installation costs will vary by platform.

Capacitive sensors have potential application in the longer term

Capacitive proximity sensors appear to have longer-term promise for reducing system costs because of their inherent simplicity. Suppliers of this technology see a readiness date of MY 2001.

Dynamic proximity sensing requires system-level investigation

All technology suppliers still face considerable development periods for implementation of *dynamic* proximity sensing in a useful form. Much of this development is unrelated to the actual sensor technology. It will have to be geared towards a systems-level understanding of the specific requirements and expected benefits and risks associated with the *use* of this dynamic information in the restraint system.

All of these technologies have demonstrated the required response speed for most dynamic applications (a few milliseconds; see Appendix C). The physical mechanism of position detection does not really limit any of these technologies, although acoustic ranging at very large occupant distances may be limited by travel-time delays. Similarly, signal processing system speed should not be an impediment, as the requirements are quite similar to those for crash severity sensing.

Hall effect safety belt sensors are available for implementation

5.2.2.6 Safety Belt Status Sensors. Advanced safety belt status sensors using magnetic Hall effect transducers have been developed to improve reliability. Contact switches are considered to be too unreliable. Most parties contacted were fairly positive about the potential and readiness of Hall effect safety belt use sensors.

Available control hardware is adequate

5.2.2.7 Computational Systems/Algorithms. In advanced systems, an electronic computer module will analyze multisensor inputs and will control restraint deployments according to a stored response matrix. It was JPL's intent to solicit information on what developments were under way to accommodate future system requirements. Our investigation has shown that, across suppliers, availability of control *hardware* is not an issue. Current microcontroller technology spans a wide portion of speed/capacity phase space.

Interestingly, many suppliers of crash sensing modules have worked at streamlining their systems to operate on the least expensive 8-bit systems. Higher capacity (16- and 32-bit) processors are readily available to handle future requirements. The lead times for these items do not impose a significant impediment.

Algorithms need further development

Advanced algorithms (software or firmware) are another issue. Nearly every full-product-line supplier and all OEMs articulated strategies for restraint deployment, based on data from their own specific set of physical sensors. There will be no difficulty in implementing the strategies as proposed on a time scale consistent with that of the sensor technology. What appears to be lacking, however, is a detailed understanding of the effects of inaccuracy, unreliability, and variability in the system's components. This will require a good deal of testing in real crash scenarios. JPL was provided no information on system-level testing procedures from any OEM or supplier.

Advanced inflator characteristics

5.2.3 Inflators. Inflators are undergoing continual development to improve the gas characteristics for air bag operation. Desirable gas characteristics include smokeless and odorless operation, cooler gas temperatures, and gases free of particulates. These environmental concerns have led to the development of non-azide propellants for inflator gas generators. Although these new non-azide propellants do offer improvements in gas characteristics, some of the new non-azide propellants produce higher gas temperatures than the sodium azide propellants and still contain some particulates. The particulates and higher gas temperatures make them less desirable for application with some of the new lighter-weight bag fabrics. Newer propellants offering smokeless/odorless operation and cooler gas temperatures are under development. Current pyro-type inflators are being modified to permit their use in depowered air bags and for dual-stage operation. Depowered inflators are being used in some current vehicles for implementation of depowered air bags to reduce inflation-induced injuries.

Two-stage inflators

Two-stage inflators permit two stages of air bag deployment depending on the severity of the crash. In some designs, the two-stage inflators are actually two separate inflators packaged as a single unit. In other designs, a single inflator has two separate propellant charges, which can be ignited separately or at the same time. The implementation of two-stage inflators is accompanied with the safety issue of disposal of the inflator after a crash in which only one of the stages of the inflator is used. This issue was not specifically discussed with industry. Therefore, their countermeasures are not known by JPL. It is possible to provide automatic disarming of the second stage after a crash, but the unit still must be removed, and the second-stage propellant must be fired or removed. Responsibility for the disposal will need to be determined. Two-stage inflators will be ready for production phase-in during 1998 by at least five suppliers.

Hybrid inflators

Hybrid inflators with pyrotechnic-augmented stored gas, as well as heated gas inflators, are in various stages of development. In pyrotechnic-augmented stored gas inflators, the gas is stored in a pressure vessel at high pressure (e.g., 20 MPa) with the exit port blocked by a burst diaphragm. The pyrotechnic charge is ignited, and the evolved gas mixes with the stored gas, causing the pressure in the vessel to increase until the burst diaphragm is ruptured and gases flow into the air bag. Hybrid inflators are being developed for both single-stage and dual-stage implementations. Some dual-stage designs will be ready for production in 1999. In some dual-stage designs, the pyrotechnic charge is divided between two separate chambers of stored gas. This design allows maximum flexibility in tailoring the inflator output for specific crash requirements. The two pyrotechnic charges can be used separately or together. In dual-stage operation, the second stage can be fired when it is determined that additional energy is required (e.g., 30 ms after the firing of the first stage). When the newer propellants are implemented with hybrid inflator designs, much more desirable gas characteristics are obtained than those obtained with current sodium azide inflators. Hybrid inflators also offer lower variability in performance than current sodium azide inflators.

Heated gas inflators

In heated gas inflators, a combustible mixture of dry air and hydrogen gas is stored in a pressure vessel under high pressure. An igniter ruptures the burst diaphragm and ignites the hydrogen–air mixture, producing nitrogen gas and water vapor. Heated gas inflators are clean and environmentally friendly, since no particulates or noxious gases are formed in the combustion process. Both single-stage and dual-stage versions of heated gas inflators are being developed. It is expected that production of heated gas inflators will begin in 1999.

Cold gas inflators

Another inflator type under development utilizes helium gas stored under high pressure. This cold gas inflator produces a low-temperature gas and is clean and environmentally friendly. The cold gas inflator incorporates a variable throttling valve which can be used to adjust the inflation rate depending on occupant characteristics. This type of inflator shows significantly lower variability than pyro-type inflators.

Development of controllable inflators

Operationally, the most significant change in future inflators will be the addition of the ability to tailor the inflator mass flow vs. time characteristics to optimize air bag deployment aggressivity and restraint force for different crash and occupant parameters. This control may be achieved through multiple staging of fixed mass flow stages or through continuously variable output inflator designs. Optimization of inflator design and operation to allow accurate variation of mass flow is an important area of current development. Near-term implementations will utilize inflators with several (two or more) fixed mass flow stages. Finally, technology is being developed to allow continuous variability of inflator mass flow in near real time.

This is a potential improvement over the quasi-static control of discrete stages.

An important consideration in establishing a deployment control strategy is inflator variability. Normally, inflators are characterized in constant volume tank tests by measuring the pressure–time history. Two parameters of importance in determining inflator performance are pressure rise rate and final pressure level. The two factors leading to inflator performance variability are ambient temperature and unit-to-unit manufacturing variability. For inflators using azide propellants, the maximum tank pressures show a variation of about 25% to 35% over the temperature range from –30°C to +80°C. The temperature sensitivity of inflators with non-azide propellants is about one-half as large as that for azide propellants. Tank pressures measured early in the inflation process show a much larger variability with ambient temperatures. This is probably due to the dependence of ignition delay and burning rate on ambient temperature. Temperature variation is significant in terms of the time required to inflate the air bag. At cold temperatures, slower bag inflation could result in delayed deployment time and/or a significantly depowered air bag. Temperature control may be needed and is feasible. In principle, compensation for this temperature variability could be obtained by changing the venting rate as a function of ambient temperature and/or providing heating in cold temperature.

Inflator variability is a problem

The unit-to-unit manufacturing variability is not easy to control. At ambient temperature, the performance variability of pyro-type inflators is due to a combination of factors, including performance of gas generant and igniter material, filter/heat sink materials, initiator, quantity of gas generant, and amount/geometry of igniter material used. For inflators using azide propellants, the unit-to-unit variation (one standard deviation) in maximum tank pressure is about ±3% at ambient temperature. The unit-to-unit variation of inflators with non-azide propellants is about one-half as large as that for azide propellants. The unit-to-unit variation (one standard deviation) in pressure rise rate is about ±10% for azide propellants and ±6% for non-azide propellants. Unit-to-unit and temperature variabilities for azide propellant systems are illustrated in Figure 5-3, which shows the nominal and 3-sigma variations for unit lots at these temperatures. The unit-to-unit variability and temperature sensitivity of current inflators are significant and could, in many cases, overshadow the potential advantages of implementing depowered or two-stage inflators.

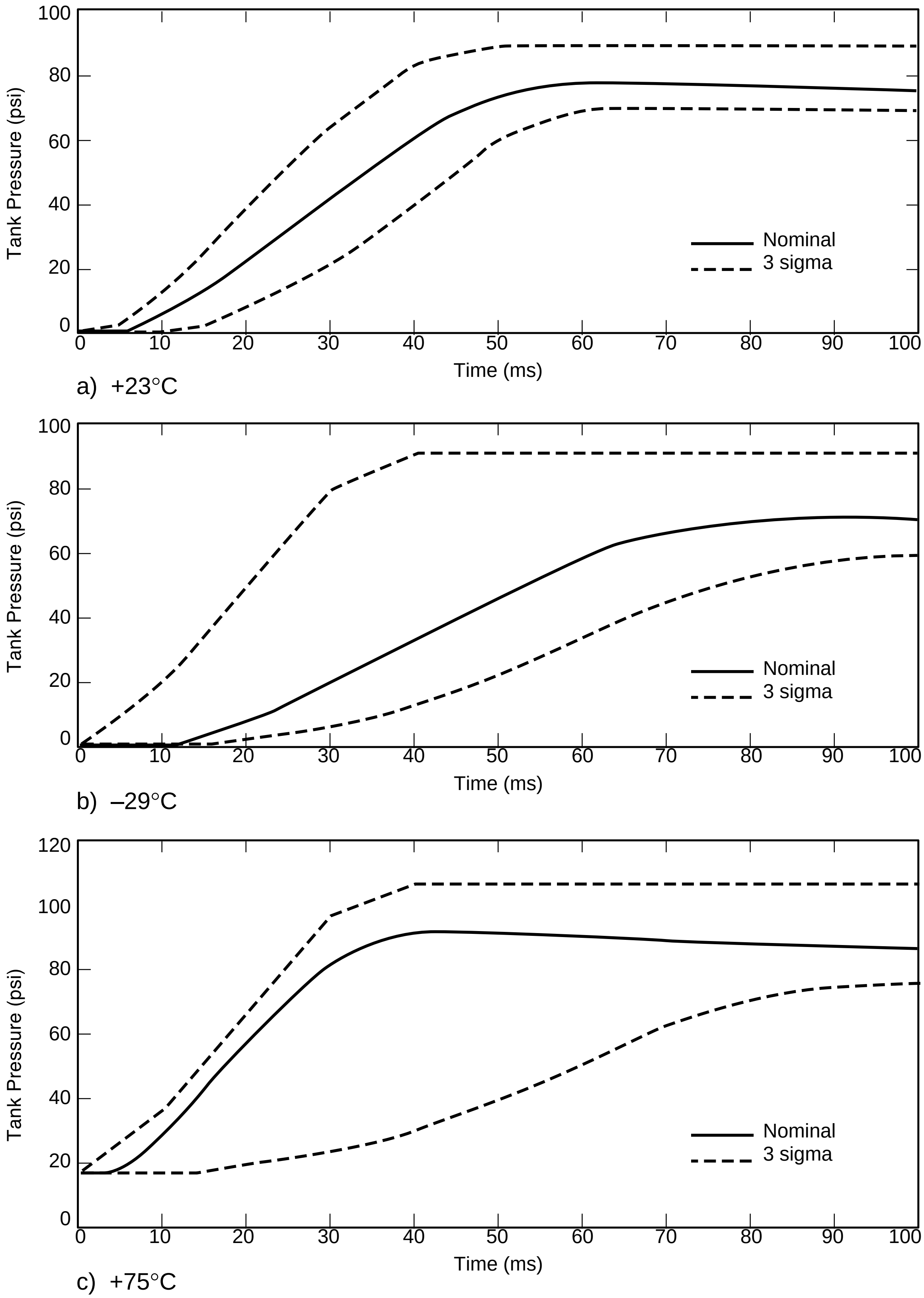

Figure 5-3. Three-Sigma Inflator Variables for Single Inflator Lots, i.e., Unit-to-Unit Variabilities as a Function of Temperature

Hybrid inflators and heated gas inflators show less unit-to-unit variability and less temperature sensitivity than do other inflator types. The maximum tank pressures for hybrid inflators show a variation of about 10% to 15% over the temperature range from –30°C to +80°C. Tank pressures measured early in the inflation process show a much larger variability with ambient temperature. For hybrid inflators, the unit-to-unit variability (one standard deviation) in maximum tank pressure is about ±1% to ±2% at ambient temperature.

Better control of inflator variability is essential to enable implementation of control strategies for advanced safety restraint systems. Variability control must begin with the design, development, and production process. Temperature compensation may be required. Active, near-real-time control of inflator output could minimize the deleterious effects of inflator variability.

Advanced inflator costs

Relative to baseline single-stage pyro inflators with azide propellants, the projected added cost of advanced inflator types is \$10–\$15 for dual-pyro inflators, \$0–\$8 for hybrid and heated gas inflators, and potentially lower cost for high-pressure stored gas inflators.

Trend toward lighter-weight fabrics

5.2.4 Air Bags. Air bag developments are moving in the direction of thinner, more pliable fabrics, lighter coatings, and simplified sewing patterns. This trend is in part to reduce cost, but it is also the application of advanced technology. Factors which influence the choice of air bag fabric include packaging volume in the air bag module, strength requirements (based on the inflator aggressiveness), and thermal requirements (based on the gas exit temperature of the inflator). Several fabric manufacturers are developing lightweight, low-permeability air bag fabrics. The light weight and low permeability will permit the use of lower-output inflators, and that, in conjunction with the lower air bag mass, should result in lower punchout forces on out-of-position occupants. The lighter-weight fabrics will simplify bag folding techniques, possibly eliminating the need for tethers. However, these lighter-weight materials are generally less tolerant of particulates and high-temperature gases. Thus, these lighter bags must be used with inflators that have lower temperatures and minimum particulates.

Bag fabrication developments

There are some development efforts in weaving technology that have produced a one-piece bag. Efforts are being made to better control the processing of woven fabrics to minimize the variability in the porosity of air bags. The focus is to provide near-zero permeability of the fabric on the front panel (i.e., the panel contacting the occupant) and to provide known porosity of the fabric on the back panel for controlled venting. Controlled air bag porosity, with low variability, could permit venting to be accomplished through the air bag fabric and eliminate the need for discrete vent holes. Other, nonwoven materials are being considered to simplify manufacturing.

New folding patterns

New folding patterns are being developed constantly, with the goal of reducing occupant interaction effects, especially for OOP occupants. One such folding pattern causes the air bag to expand radially during deployment, putting much less force against an OOP occupant. This folding pattern results in a reduced packing efficiency, making it a challenge to pack it into some new driver side air bag modules.

New tether designs also are also being developed. These new designs will permit earlier loading of the tether, thereby reducing the energy transmitted to an OOP occupant.

Compartmented air bags show promise

New bag shapes and designs are being developed to reduce the loading of OOP occupants. Air bags with multiple compartments are being developed, the potential benefit being that the different chambers can be pressurized sequentially, in order to maintain sufficient restraint force. The first compartment can be pressurized much quicker than a full-sized bag to provide some early occupant protection. When the pressure in the first compartment reaches a predetermined level, a port into the second compartment (a tear strip or perforated port) opens to begin filling the second compartment at the predetermined pressure level. Air bag concepts with the compartments arranged axially and radially as well as bags within bags are under development. The bag-within-a-bag configuration was developed and demonstrated for 80 km/h (50 mph) occupant crash protection by Minicars, Inc. in the late 1970s and early 1980s. It showed good performance in tests by NHTSA. Compartmented air bag designs could be ready for production by the year 2000.

Venting

Air bag venting systems are designed to be used in conjunction with a combination of air bag volume, inflator performance, and desired venting characteristics. Suppliers are evaluating multilevel and continuously variable venting designs for use with future air bags. Used in conjunction with appropriate occupant sensors, these designs could control venting as a function of occupant type and position. Current venting is achieved through constant area vents that are continuously open and/or through porous bag material. Some venting designs under development utilize no venting during the initial bag-filling process until a predetermined bag pressure is achieved. At that time, a constant-area venting port opens to provide venting for the remainder of the deployment event. The port (e.g., a tear strip or perforated port) is designed to open at a predetermined pressure level. This system will be in production in 1998. As with inflators, a longer-term goal of providing real-time, variable bag response has been put forward by several suppliers and OEMs.

JPL did not investigate some advanced developments

5.2.5 Future Supplemental Safety Restraint Development. In the future, more vehicles are likely to have additional supplemental restraint systems such as air bags for side impact, rollover, and knee bolster functions. Technologies to improve the performance of air bags and inflators continue to evolve. Suppliers are also studying potential improvements in air bag packaging techniques. JPL did not investigate these developments in depth.

Safety belt systems can be improved

5.2.6 Safety Belt Systems. Belt makers are developing several performance enhancing features for three-point seat belt systems. These include belts with high initial stiffness, high-output pretensioners, and variable load-limiting devices.

Pretensioners

High initial belt stiffness, coupled with high-output pretensioners, generates a high degree of coupling early in the crash between the occupant and the passenger compartment or seat. One benefit of this is to maximize the ride-down distance for dissipation of the occupant's kinetic energy. Higher belt stiffness is gained through the use of low-elongation webbing, short belt loops, rigidized belt anchorages, and new seat belt geometries (including four-point harnesses). Higher-output pretensioners also increase the initial stiffness of the primary restraint system. Providing this high force over longer stroke lengths is a key to improving occupant coupling to the seat for a wide range of initial occupant positions. To this end, longer stroke pretensioners are under development.

Load limiters

Variable load-limiting devices are tuned to provide a constant force level over the maximum occupant excursions. Present concepts use single and even dual levels (which are preset). Concepts exist for continuously variable load limiters, in which the force level could be adjusted by the control system based upon information about occupant mass and position provided by the system sensors.

Seat design

By initially coupling the occupant to the seat (e.g., with pretensioners), the capability exists for using or adjusting the mechanics of the seat itself to dissipate kinetic energy. This approach requires seat belts that are integrated with the seat as opposed to belts with attachment points on the vehicle pillars. Concepts have been developed for improving occupant energy management through tuning the initial stiffness of the seat, controlling seat attachment forces, and integrating belts into the seats.

Air belts are a promising technology to be investigated further

Finally, seat belt designs with inflatable elements (air belts) are being developed. The inflatable element augments the standard three-point seat belt system by inflating the shoulder-belt portion of the belt during impact. In one concept, the fabric of the inflatable element decreases in length when inflated. Thus, the inflatable element also pretensions the seat belt. Air belts are likely to be less aggressive than air bags because they do not expand with great force toward the occupant.

At this time, no suppliers or OEMs are considering potentially more effective safety belt designs, such as four-point harnesses.

Studies have shown that systems that combine the implementation of advanced belts, pretensioners, load limiters, and air bags offer the potential for enhanced protection.

5.2.7 Manufacturing Considerations. Manufacturing, production quality control, and other related considerations, although important, were secondary issues relative to performance in this assessment. A detailed evaluation of manufacturing issues was beyond the scope of this assessment. Manufacturing issues affect the technology costs and availabilities. None of the suppliers mentioned manufacturing differences between technologies as significant factors, other than their effect on cost and availability. Manufacturing considerations are imbedded in these values. Some suppliers have indicated that manufacturing requirements will lead to phased implementation of advanced technology.